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ABSTRACT

Purpose: To examine the extent to which the classical physiological variables of endurance running performance [VO_{2max}, $\%VO_{2max}$ at ventilatory threshold (VT), and running economy (RE)], but also muscle strength factors contribute to short trail running (TR) performance. **Methods:** A homogeneous group of nine highly-trained trail runners performed an official TR race (27-km) and laboratory-based sessions to determine VO_{2max}, $\%VO_{2max}$ at VT, level RE ($RE_{0\%}$) and RE on a +10% slope ($RE_{+10\%}$), voluntary concentric and eccentric knee extension torques (MVC_{Con} and MVC_{Ecc}, respectively), local endurance assessed by a fatigue index (FI) and a time to exhaustion at 87.5% of the velocity associated with VO_{2max}. A simple regression method and commonality analysis identifying unique and common coefficients of each independent variable were used to determine the best predictors for the TR race time (dependent variable). **Results:** Pearson correlations showed that FI and VO_{2max} had the highest correlations (r = 0.91 and r = -0.76, respectively) with TR performance. The other selected variables were not significantly correlated with TR performance. The analysis of unique and common coefficients of relative VO_{2max}, $\%VO_{2max}$ at VT and $RE_{0\%}$ provides a low prediction of TR performance (R^2 = 0.48). However, adding FI and $RE_{+10\%}$ (instead of $RE_{0\%}$) markedly improved the predictive power of the model (R^2 = 0.98). FI and VO_{2max} showed the highest unique (respectively 49.7 and 21.0% of total effect) and common (27.0% of total effect) contributions to the regression equation. **Conclusions:** The classic endurance running model does not allow meaningful prediction of short TR performance. Incorporating more specific factors to TR such as local endurance and gradient-specific RE testing procedures should be considered to better characterize short TR performance.

Key words: muscle strength, running economy, maximal oxygen uptake, endurance, training, trail running

INTRODUCTION

Paragraph 1. The International Trail Running Association defines Trail-running (TR) as "a pedestrian and off-road race conducted in a natural environment (e.g. mountain) with minimal possible paved or asphalt road (<20% of the total duration race)". Classically, TR races are performed on mountain single tracks including positive and negative elevation with repeated technical sections on rocky and root-covered paths. TR profiles may extend from short (<42 km) to ultra-long (>100 km) distances. In TR races, in which popularity has markedly increased during the last decade (1,2), the performance (race time) among the best runners usually ranges between 1.5 to 4-h for a short distance race of 20 to 42 km.

Paragraph 2. The main difference between short TR races and more conventional, on-road, running events (i.e. level road profile) such as the marathon is that TR races are characterized by successive uphill and downhill off-road sections, leading to major changes in physiological and mechanical responses (*for review*, (1)). In such cases, prolonged and intense concentric and eccentric actions occur in lower limb muscle-tendon units during uphill and downhill sections of TR events, respectively (3). The modality of muscle action and the contraction time are specific to TR sections and differ from level road running, which is mainly characterized by repeated and continuous stretch-shortening cycles for lower limb extensors (4). Dewolf et al. (5) recently showed that the classic mechanical model of level running clearly differs from incline conditions. Specifically, during level running, the upward and downward movements of the center of mass are overall equal, as are the positive and negative external work within each step. In contrast, during incline running, the "bouncing" mechanism gradually disappears as speed and slope increase (5). On positive slopes, the step period and the downward movements of the body are reduced while on negative slopes the step period increases and the upward movement decreases. Major changes in ground reaction forces are also apparent from a steep downhill to a steep uphill: the normal impact force peaks and the parallel braking force peaks decrease while the parallel propulsive force peaks increase (5,6). Therefore, repeated changes in slope and associated mechanical responses during TR likely influence the modality of muscular contraction and metabolic demand (*for review*, see (1,7)).

Paragraph 3. In a recent review, Giandolini et al. (1) reported that central and peripheral mechanisms of muscle fatigue as well as mechanical muscle damage largely contributed to the decline of TR performance. During uphill sections, predominantly concentric muscle contractions induce less mechanical stress and thereby, less potential muscle damage. Excitation-contraction failures reported after uphill running seem mainly due to the high exercise intensity required (1). In contrast, a marked decline in maximal voluntary contraction (MVC) torque (> -15%) for plantar flexor and/or leg extensor muscles has been reported following treadmill and outdoor downhill running exercises (8,9). Although central fatigue might play an important role in the MVC decline, especially in prolonged exercises (1), studies investigating short distance TR or downhill running modalities report clear decreases in both central and peripheral fatigue-related parameters (3,8–10). For instance, Vercruyssen et al. (10) recently reported a ~4.5-6.5% decrease in quadriceps voluntary activation (i.e. central component) associated with a significant reduction in the low-to-high frequency doublet ratio (i.e. peripheral component) after various 18.6-km TR sessions performed close to race intensity. Thus, the severe muscular alterations induced by isolated downhill sections or simulated TR events contribute to intense and prolonged fatigue and suggest that muscle strength and/or resistance to fatigue is an important factor in the understanding of short TR performance.

Paragraph 4. Although muscular actions differ between TR and level road running, the duration of short TR races reported in trained runners is comparable to that observed during half-marathon or marathon events (< 4-h). For these endurance events, it is classically accepted that the key physiological determinants of performance include maximal oxygen uptake (VO_{2max}), the percentage of VO_{2max} (%VO_{2max}) that can be sustained during running - which has been shown to be closely linked to the lactate threshold (LT) - and running economy (RE, expressed as energy cost), i.e. the metabolic energy spent per unit of distance covered (11–16). The relationship between each one of these physiological variables and level running performance has been widely studied. For instance, Costill et al. (14) reported a strong negative correlation (r = -0.91) between VO_{2max} and 10-mile race time in runners who varied greatly in VO_{2max}. Similarly, LT was also highly correlated ($r \geq 0.91$) with performance on running distances ranging from 3.2 to 42.2 km (15). Finally, McLaughlin et al. (16) recently reported a high correlation (r = 0.81) between RE and 16-km time in well-trained distance runners. As a result, these three variables (VO_{2max}, % VO_{2max} at LT, and RE) have been often used in a classical physiological model of endurance running performance (12,17). Given the specific muscle actions in TR, it would be interesting to know whether these physiological determinants of level running are also related to short TR performance.

Paragraph 5. As described above, it is well established that differences in RE explain a great part of the inter-individual variability in running performance among athletes with similar

VO_{2max} values (18). In this regard, improved RE is associated with better marathon performance in world-class marathon athletes, independent of changes in VO_{2max} (19). However, to elucidate whether RE plays a similar role in short TR, dissimilar to level road running in terms of terrain and pacing, a specific investigation of the relationship between RE and TR performance is necessary. When focusing on RE responses to slope conditions on a treadmill, Balducci et al. (20) recently reported that level RE was not correlated with RE measured on positive slopes (12.5 and 25%). Conversely, RE values at 12.5 and 25% were well correlated (r = 0.75), suggesting that specific mechanisms are active in determining RE on inclines and preserved throughout different gradients. Interestingly, a recent study focusing on physiological and biomechanical determinants of uphill mountain marathon performance (21) showed that RE was significantly correlated with overall race time and that athletes with smaller changes in RE during the race also had greater maximal lower limb power. This is in line with previous studies that emphasize the importance of lower limb muscle strength and specific strength training (e.g. uphill bouts, resistance) to improve RE and in turn, running performance (11,21). Based on these reports and considering the impairment in muscle strength consistently observed after simulated TR events or races (3,22,23), the implication of factors associated with muscular strength might be expected in short TR performance.

Paragraph 6. The objective of this study was therefore to identify the physiological determinants of short TR performance using the classic endurance performance model (16) and including specific factors to TR such as local endurance or uphill RE. Given the differences in muscle contraction modalities and race profiles between TR and level road running, we hypothesized that the predictive power of a commonality regression analysis using the classical model of endurance running would increase through inclusion of TR-specific factors (e.g. local endurance, uphill RE) in a homogeneous group of highly trained trail runners.

METHODS

Subjects

Paragraph 7. Nine experienced, high-level male trail runners (age: 39 ± 8 [mean ± SD] years; height: 1.73 ± 0.06 m; body mass: 68.4 ± 5.8 kg) volunteered to participate in this study. Recruitment was based on the performance level within national and regional short distance TR races, with subjects consistently ranking in the first 20 finishers. Participants had a mean of 8.5 ± 2.1 years of TR experience and a mean weekly running mileage of 75 ± 6 km completed on 3-5 $d \cdot wk^{-1}$. Furthermore, based on their training log, subjects also performed a minimum of 5 cycling sessions per month (~250-350 km) including specific uphill bouts (~2000-3000m of cumulated positive elevation). Subjects gave their informed written consent to participate in this study, which was approved by the local ethics committee for the protection of individuals and conducted according to the Declaration of Helsinki.

Experimental design

Paragraph 8. Experiments were conducted within a 21-day period including laboratory sessions (separated by at least 72-h) and the TR race (Figure 1). On five separate occasions each participant completed: (i) a maximal test performed on a motorized treadmill with +10% slope (Gymrol; HEF Tecmachine, Andrézieux-Boutheon, France) to determine VO_{2max}, velocity associated with VO_{2max} (vVO_{2max}), maximal heart rate (HR_{max}) and ventilatory threshold (VT), (ii) a submaximal treadmill running test to measure RE at various velocities and slopes, (iii) muscle performance tests to determine MVC in concentric and eccentric muscle modes and local endurance of the knee extensors, (iv) a treadmill run time to exhaustion (TTE) and (v) an official TR race to determine running performance as the total racing time. For all running conditions conducted in laboratory, VO_2, carbon dioxide production (VCO_2) and minute ventilation (V_E) were analyzed breath-by-breath and every 10-s by an Oxycon Alpha metabolic measurement cart (Jaeger®, Germany).

INSERT FIGURE 1 HERE

Maximal running test

Paragraph 9. Subjects started running on a treadmill at a velocity of 7 $km.h^{-1}$ which increased by 1 $km.h^{-1}$ every 2 min until exhaustion. During the maximal test, the slope was fixed at +10% to better represent the characteristics of TR training and racing (10), although it was recently reported that treadmill slope has no impact on the determination of relative VO_{2max} in endurance mountain runners (20). According to *ACSM's Guidelines for Exercise Testing and prescription*, VO_{2max} was considered to have been achieved if there was no increase (<100 $ml.min^{-1}$) in VO_2 with an increase in treadmill speed or if the following criteria occurred at the end of exercise: respiratory exchange ratio (RER) > 1.15 and subjects reached their age-predicted HR_{max} (220-age). All tests were terminated at volitional exhaustion, and all subjects achieved VO_{2max} by these criteria. VO_{2max} was averaged using the three highest consecutive values (i.e. over a 30-s interval) reached during the last stage of the maximal running test. For each subject, the 30-s interval enabling the VO_{2max} determination was used to identify vVO_{2max}. Finally, VT was determined as the point at which an increase in V_E/VO_2 was observed with no concomitant increase in V_E/VCO_2 (24).

Running economy

Paragraph 10. A standardized 10-min warm-up (5-min level and 5-min uphill running at 2.77 and 2.08 $m.s^{-1}$, respectively) was performed before the RE test. Subsequently, each subject completed, in random order, two 5-min running stages at two different speeds and slopes, with a 5-min rest (in a seated position) between stages: 3.88 $m.s^{-1}$ (0% grade, $RE_{0\%}$) and 2.5 $m.s^{-1}$ (+10% grade, $RE_{+10\%}$). VO_2 values were measured continuously with the metabolic cart during the 5-min running tests and averaged over the final 2-min to calculate RE values. RE at each speed was expressed as a caloric unit cost ($J \cdot kg^{-1} \cdot m^{-1}$) (25). The level speed was determined from pilot testing conducted in three subjects of the present study and fixed at 3.88 $m.s^{-1}$ to be close to the relative intensity (~80%VO_{2max}) reported by McLaughlin et al. (16) in their model of level running performance. Similarly, uphill speed was chosen to reproduce a metabolic intensity close to that expected at level running, but also to reflect the metabolic demand induced during the uphill sections of short distance TR races. Thus, the percentage of VO_{2max} reached by subjects during level RE and uphill RE tests was 81.3 ± 6.9 and 82.6 ± 7.5%, respectively.

Muscle strength factors

Paragraph 11. Subjects were familiarized with all procedures concerning muscle force testing on their first visit to the laboratory. Muscle force characteristics of the right knee extensors were evaluated using (i) maximal voluntary concentric and eccentric torques (MVC_{Con} and MVC_{Ecc}, respectively) and (ii) a local endurance test. During these tests, participants were securely strapped into an isokinetic dynamometer (Biodex system 3, Shirley, New York, USA) with a knee joint angle of 90° (full leg extension = 0°) for the assessed (right) leg. The axis of the knee joint was carefully aligned with the rotational axis of the dynamometer and all settings were kept constant throughout the experiment. Before each MVC_{Con} and MVC_{Ecc}, participants warmed up on the isokinetic dynamometer by repeating 10 one-second submaximal concentric or eccentric contractions (one second rest between contractions). After 2 min rest, two MVC_{Con} or MVC_{Ecc} (angular velocity = $60°s^{-1}$) were performed for the full range of motion, each lasting around 4-5 s (55 s rest between attempts). Strong verbal encouragement was given and torque was visually displayed. MVC_{Con} and MVC_{Ecc} tests were conducted in random order and a 10-min rest was granted between MVC modalities. The highest MVC_{Con} and MVC_{Ecc} achieved during the two attempts was retained for analysis.

Paragraph 12. The local endurance test was conducted 15-min after MVC_{Con} and MVC_{Ecc} testing. Following a standardized warm-up consisted of submaximal concentric contractions, subjects performed 40 consecutive maximal concentric contractions (angular velocity = $60°.s^{-1}$) of the knee extensors over their full range of motion (i.e. from full knee flexion to full knee extension) (26). Following full extension, subjects were instructed to relax during the flexion phase of the cycle, while the isokinetic machine arm returned to full flexion position ($60°.s^{-1}$). Local endurance was assessed through a fatigue index (FI) expressed in %: FI = 100 - [(last 5 repetitions/first 5 repetitions) × 100] (26). FI was therefore determined by averaging maximal concentric torque values recorded at the start and at the end of local endurance test only in the knee extension phase (Figure 2).

INSERT FIGURE 2 HERE.

Run time to exhaustion

Paragraph 13. Subjects were requested to perform the same warm-up routine as for the RE tests. Immediately after the warm-up, a relative velocity corresponding to 87.5% VO_{2max} was set on the treadmill at +10% slope and the subjects ran until they could no longer maintain the required velocity. Based on pilot testing, this velocity was selected to obtain running times between 10 and 15-min. This running intensity was chosen to induce fatigue in less than 15 minutes with major aerobic contribution to running performance. The run time to exhaustion was measured using a manual stopwatch to the nearest second from the moment the participant released the handrail until he pushed on the security button fixed on the handrail. All subjects received strong verbal encouragement to continue as long as possible.

Trail running race

Paragraph 14. Running performance was determined from an official short distance TR race (December 2012, South-East of France, total number of participants: 120) with a medium elevation to distance (E/D) ratio of 51.9 (1400 m positive elevation for 27 km total distance). The TR race was exclusively run on mountain single tracks with repeated technical rocky sections. All subjects wore a cardio-GPS watch (RS800CX, Polar, Kempele, Finland) during the TR race for continuous HR and speed monitoring. Although different refueling points were available during the TR race, subjects were free to carry light backpacks or drinking belts containing fluids or carbohydrates (e.g. drinks, gels, bars).

Statistical analysis

Paragraph 15. All data are expressed as mean ± standard deviation (SD). Pearson's correlation test was used to determine which of the variables measured during the laboratory sessions was the best predictor for running performance defined as TR race time. Only for this analysis, an alpha of $P \leq 0.05$ was considered statistically significant. Given the limitations related to the stepwise regression method, especially the overlapping variance attributed to the individual predictors, Nathans et al. (27) have suggested alternative multiple regression methods to assess each variable's importance in a prediction model. The commonality regression analysis was implemented here to identify unique and common effects (i.e. commonality coefficients) of each predictor (independent variable) on the dependent variable (27,28); in this case TR race time as a measure of performance. Briefly, unique effects identify how much variance is unique to an observed variable or total effect (i.e. no shared variance with other independent variables), and common effects identify how much variance is common to groups of variables (i.e. shared variance or "overlap" in independent variables) (27). Finally, negative commonality coefficients occur in the presence of suppressor effects when some of the independent variables affect each other in the opposite direction (28).

RESULTS

Paragraph 16. The subjects' average race time was 2 h 58 min 49 s ± 10 min 35 s, which corresponds to an average running speed of 9.42 ± 0.55 $km.h^{-1}$. Their relatively high level of performance was shown by their final ranking between the 2^{nd} and the 16^{th} place but also, VO_{2max} responses ranging from 61.1 to 69.7 $ml.min^{-1}.kg^{-1}$. On average, the relative metabolic intensity sustained during the TR race represented 89.8 ± 2.8 % HR_{max}. Mean run time to exhaustion was 773 ± 266 s (range: 552 to 1403 s). RE and muscle strength parameters are presented in Table 1.

INSERT TABLE 1 HERE

Paragraph 17. The simple Pearson product–moment correlations of physiological variables with TR performance are listed in Table 2. Based on this statistical analysis, FI and relative VO_{2max} showed the highest correlations with the TR race time, whereas the $\%VO_{2max}$ at VT, $RE_{0\%}$ and $RE_{+10\%}$ were not correlated. Mean values in vVO_{2max} (r = -0.75; P = 0.03) were also associated with the TR race time. Conversely, no significant association was found between the TR race time and MVC_{Con} (r = 0.27; P = 0.52), MVC_{Ecc} (r = -0.22; P = 0.60) or run time to exhaustion (r = -0.39; P = 0.29). Additional simple correlations indicated that after controlling for body mass, VO_{2max} was not associated with $RE_{0\%}$ (r = 0.61; P = 0.06) or $RE_{+10\%}$ (r = 0.38; P = 0.28). Finally, run time to exhaustion was not significantly correlated with $RE_{0\%}$ (r = -0.50; P = 0.21) or $RE_{+10\%}$ (r = -0.37; P = 0.36).

INSERT TABLE 2 HERE

Paragraph 18. Unique and common effects of each independent variable were assessed using the commonality analysis (Table 2). A first statistical analysis was applied to the classic endurance running model, which produced a model summary with a total coefficient of R^2 = 0.48 (Figure 3) - a low predictive power. In this analysis, relative VO_{2max} alone accounted for 90.2% of the total regression effect. However, a second commonality analysis was applied and included

TR-specific factors such as FI and $RE_{+10\%}$ (Figure 3). In this case, the commonality matrix identified the best predictive model with total R^2 = 0.98 from the use of relative VO_{2max}, FI and $RE_{+10\%}$, as independent variables. In total, these three predictors uniquely accounted for 76.4% of the total R^2. The remaining 23.7% was due to the variance that the sets of predictors shared in common with TR race time. The most noticeable common effect observed was between FI and VO_{2max}, which accounted for 27.0% of the regression effect. The percentage of unique and common contributions of each independent variable to the total R^2 is detailed in Figure 3.

INSERT FIGURE 3 HERE

DISCUSSION

Paragraph 19. The objective of this study was to identify the physiological determinants of short TR performance based on the classic model of level running performance. Using a commonality regression analysis, the major result of this study is that the classic endurance performance model does not explain short TR performance in a homogeneous group of trained trail runners. The novelty of this study is that the inclusion of factors more representative of TR such as local endurance and $RE_{+10\%}$ improved the predictive power of the model and herewith provides new insights into the analysis of short TR performance.

Paragraph 20. In this investigation, the commonality regression analysis showed that laboratory-based physiological measures from the classic endurance running model explained only 48.1% of the total variance in TR performance (Figure 3). As a consequence, various suppressor effects were identified through combinations between the three predictors selected in the model (Table 2), which tends to indicate that the amount of variance in the regression effect (total R^2) is confounded by a set of independent variables (28). Although it is acknowledged that relative VO_{2max}, $\%VO_{2max}$ at LT and RE are the three primary physiological factors in well-trained distance runners (13,16–18), the importance of these variables in determining running performance may depend on the degree of homogeneity in the population studied (e.g. characterized by relative VO_{2max} responses and/or performance level). For instance, using a stepwise regression, model McLaughlin et al. (16) reported a strong prediction of a 16-km time trial performance (97.3%) from relative VO_{2max} and RE variables in well-trained male and female distance runners. These results are in agreement with those previously reported over a longer distance running event (17). In this specific context, the flatter the running surface (i.e. road), the higher the relevance of laboratory-based physiological measures of relative VO_{2max}, $\%VO_{2max}$ and RE. Many findings focusing on predictors of running performance have been observed within heterogeneous cohorts of well-trained runners (e.g. (16,18)). However, the physiological variables used in the classic endurance running model might have lower predictive value when the recruited population is highly trained and relatively homogeneous in term of performance level (29,30). For homogeneous groups, it has been reported that other predictive variables were more appropriate to better describe running performance. In addition, the specificity of the running course profile (i.e. rough terrain) may have also influenced the predictive power of the classic model. In the present study, the profile of the TR race featured positive and negative changes in elevation over rocky and uneven terrain, and contrary to more conventional running events, flat sections were scarce (Figure 1). In TR, prolonged concentric and eccentric muscle actions during uphill and downhill sections are known to induce specific mechanical and metabolic alterations (*for review*, (1)), which could partly explain why the traditional model of endurance running is less appropriate for predicting TR performance based only on the classic physiological determinants.

Paragraph 21. Within this framework, incorporating local endurance (as assessed with the FI variable) into the model significantly improved the predictive power, uniquely accounting for 49.7% but also, 27.0% in shared variance with relative VO_{2max} of the total (R^2 =0.98, Figure 3). The common effects identified between these two predictors indicate how particular sets of variables operate in combination in predicting TR performance, possibly generating recommendations regarding how to jointly target these two variables to produce desired effects. To our knowledge, this is the first study to highlight the importance of local endurance in short TR performance, even within a homogeneous group of trained athletes. Our results showed that trail runners with the highest local endurance (as assessed by a lower FI) had better TR final race times. Based on a previous study (31), it is likely that greater local endurance could limit the extent of any change in muscle recruitment and/or coordination and might have a potential regulatory role in fatigue development and in turn, on TR performance. Interestingly, additional results also showed a strong and positive correlation between FI and the cumulated UHR times over TR sections (Figure 4). Collectively, these results suggest that local endurance is a key physiological determinant of TR race time and performances especially in UHR sections.

INSERT FIGURE 4 HERE

In the present work, local endurance was assessed through a FI variable calculated from repeated maximal concentric contractions of the knee extensors, i.e. the modality of muscle action that is dominant in UHR sections but also during cycling or cross-country mountain bike exercises. As detailed in the “Methods” section, trail runners frequently use the latter activities in their training programs during specific uphill sessions. We suggest that the greater local endurance observed in the trained trail runners studied here may result in chronic muscular adaptations induced by specific uphill training, which in turn, probably contributes to improved UHR and total TR race times.

Paragraph 22. The relationship between local endurance and TR race time provides a new practical insight into the comprehensive approach of short TR performance. Nevertheless, FI was the only significant strength variable correlated with the TR race whereas maximal strength capabilities including MVC_{Con} and MVC_{Ecc} showed a poor correlation. Only few studies are available about the relationship between muscle performance (e.g. muscle strength and power) and off-road running performance (21,32). In these recent investigations focusing on uphill marathons, the major findings indicated that runners with greater maximal mechanical power of lower limbs demonstrated smaller changes in running mechanics or lower fatigue-induced alterations in RE. Consequently, it has been suggested that specific power training of the lower limbs may contribute to the improvement of uphill marathon performance. Collectively, these results support the importance of muscle strength capacity and endurance in determining off-road running performance. In terms of training content, there is an interest for trail runners to include uphill cycling sections and local endurance training (11).

Paragraph 23. Furthermore, the simple Pearson product-moment correlations showed that relative VO_{2max} and vVO_{2max} were related to TR performance (r = -0.75 and r = -0.81, respectively, Table 1). The finding regarding vVO_{2max} is in agreement with previous investigations about factors affecting running performance (e.g. (16,33)). Although no specific test was used to determine vVO_{2max} in the current study, it would be interesting to determine this variable from a treadmill running protocol which has been previously used (16) to better characterize the aerobic profile of trail runners. Indeed, it is well-known that reaching a high vVO_{2max} can be accomplished by having either a high VO_{2max} or an improved RE (e.g. (16)). Additionally, a high correlation between these two variables ($r > 0.8$) has consistently been observed among distance runners (12,14,34) over many years. In the present study, the correlation obtained between relative VO_{2max} and TR performance was lower than those previously reported in distance runners who were greatly heterogeneous in terms of relative VO_{2max} responses (e.g. (12,14)). This difference could be due, in great part, to the higher homogeneity in our experimental group (VO_{2max} values ranging from 61.1 to 69.7 $ml.min^{-1}.kg^{-1}$). Consequently, these results support the idea that relative VO_{2max} is an important factor in determining running performance (road or TR events), whether the studied population is heterogeneous or not.

Paragraph 24. In contrast, our results showed a poor correlation between $\%VO_{2max}$ at VT or $RE_{0\%}$ and TR race time (Table 1). The $\%VO_{2max}$ at VT or LT is not systematically a reliable predictor of running performance. Indeed, McLaughlin et al. (16) found a non-significant correlation ($r = 0.13$) between $\%VO_{2max}$ at LT and 16-km running performance in trained distance runners, probably due to the low variability of this physiological variable observed in this group of distance runners. Similarly, the low variability of runners' $\%VO_{2max}$ at VT reported in this study might explain the lack of a clear relationship with TR race time. Moreover, the finding that $RE_{0\%}$ was not related to TR performance is in line with earlier studies conducted in

Kenyan or non-elite European runners (29,35). We assume that, in this homogeneous group of trained runners, the relative importance of RE is lowered by other factors such as FI and VO_{2max} to maintain high performance levels. It has been postulated in a large cohort of highly trained distance runners that a slight positive relationship (r = 0.25) exists between RE and VO_{2max} when body mass is appropriately accounted for (36). In the present study, however, correlation analysis controlling for body mass revealed no relationship between VO_{2max} and $RE_{0\%}$, suggesting that RE and VO_{2max} are primarily determined independently.

Paragraph 25. The major drawback in translating the classic endurance running model to off-road races was the traditional evaluation of RE based on a level treadmill protocol. The determination of RE specific to TR incline ground constraints might provide an improved predictive power of the model in off-road runners. This is supported by the better total R^2 when including $RE_{+10\%}$ in the model (Figure 3). Since the expression of RE as a caloric unit cost (in $kcal \cdot kg^{-1} \cdot km^{-1}$) has been suggested to be more sensitive to changes in relative speed than RE expressed as O_2 unit cost (25), it would be interesting to calculate an average caloric unit cost specific to TR including at least two running velocities or relative intensities set at level ground, downhill and uphill. Moreover, our findings also indicated that better treadmill time to exhaustion were associated with improved $RE_{0\%}$ (r = -0.85) and $RE_{+10\%}$ (r = -0.73), suggesting the importance of determining RE on a surface/slope on which runners can reproduce a running pattern representative of that produced in field conditions. Using a telemetric system, Jensen et al. (37) reported that orienteering athletes who included uneven terrain sessions in their daily training demonstrated superior RE on this type of surface than track runners who trained on flat roads. Recently, in a group of elite and amateur orienteering athletes, Hébert-Losier et al. (38)

reported a lower correlation between laboratory-based RE measures and 2-km time trial performance when the field test was performed in a forest-path compared to road condition. Collectively, these results suggest that using steep inclines and/or uneven terrains during field-based RE testing procedures may lead to a more realistic/relevant assessment of physiological factors. Another limitation of this study is the small sample size of the population, explained by the selective recruitment of highly-trained athletes with extensive TR experience. This resulted in homogeneous relative VO_{2max} values and TR race times. These criteria are relatively unique in the analysis of short TR races and may be compared to off-road studies using small groups of elite athletes (e.g. (20,38)).

Paragraph 26. In conclusion, the findings of this study indicate that the classic physiological model of endurance running does not allow the successful identification of physiological predictors for short TR performance within a homogeneous group of trained trail runners. However, the predictive power of the model was markedly improved when incorporating more specific factors to TR such as local endurance or RE measured in a positive slope condition. Although this study provides a new insight into the comprehensive approach of short TR performance, future studies should include field-based RE testing procedures and various local endurance tests specifically under concentric and eccentric conditions.

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FIGURES CAPTIONS

FIGURE 1. Graphic representation of experimental conditions. VO_{2max}: maximal oxygen uptake; vVO_{2max}: velocity associated with VO_{2max}; VT: ventilatory threshold; $RE_{0\%}$ and $RE_{+10\%}$: running economy at level ground and +10% slope, respectively; MVC_{Con} and MVC_{Ecc}: maximal voluntary concentric and eccentric contraction torques; FI: fatigue index; TTE: run time to exhaustion, TR: trail running.

FIGURE 2. Data from the local endurance test: the left panel (A) shows the individual decrements of peak concentric torque during the muscular endurance test. The grey bars represent each individual's mean of two maximal voluntary concentric torques ($AverageMVC_{Con}$). The black dots represent the first three concentric torque peaks recorded at the beginning of the local endurance test and the white dots show the last three concentric torque peaks recorded at the end of the test. Each individual's torque loss throughout the test is illustrated with a black dotted line. The right panel (B) shows a representative individual’s torque trace with a magnified extract in which flexion (recovery relaxation phase) and extension (active contraction phase) are indicated along with the position of the Biodex arm (black dotted line). The bottom right window shows the entire local endurance test (40 full cycles inducing a decrease in peak torque) for reference. All values used in this graph are absolute torque values.

FIGURE 3. Graphic representation of commonality regression models for predicting TR performance. Panel A: commonality analysis for the classic endurance running model. Panel B: commonality analysis for the adapted and specific model to TR. Single arrows, dashed lines

(double arrows) and external dotted lines represent respectively the contribution-percentage of unique, common to two factors, and common to all factors for each independent variable in the total regression effect (i.e. R^2). Negative values indicate a suppressor effect between independent variables. The sum of common and unique effects for each model corresponds to the total regression effect (i.e. total R^2).

FIGURE 4. Relationship between cumulated uphill running (UHR) or cumulated downhill running (DHR) times and trail running (TR) performance (Panel A), but also between UHR times and fatigue index (FI, in %) (Panel B).

Figure 1

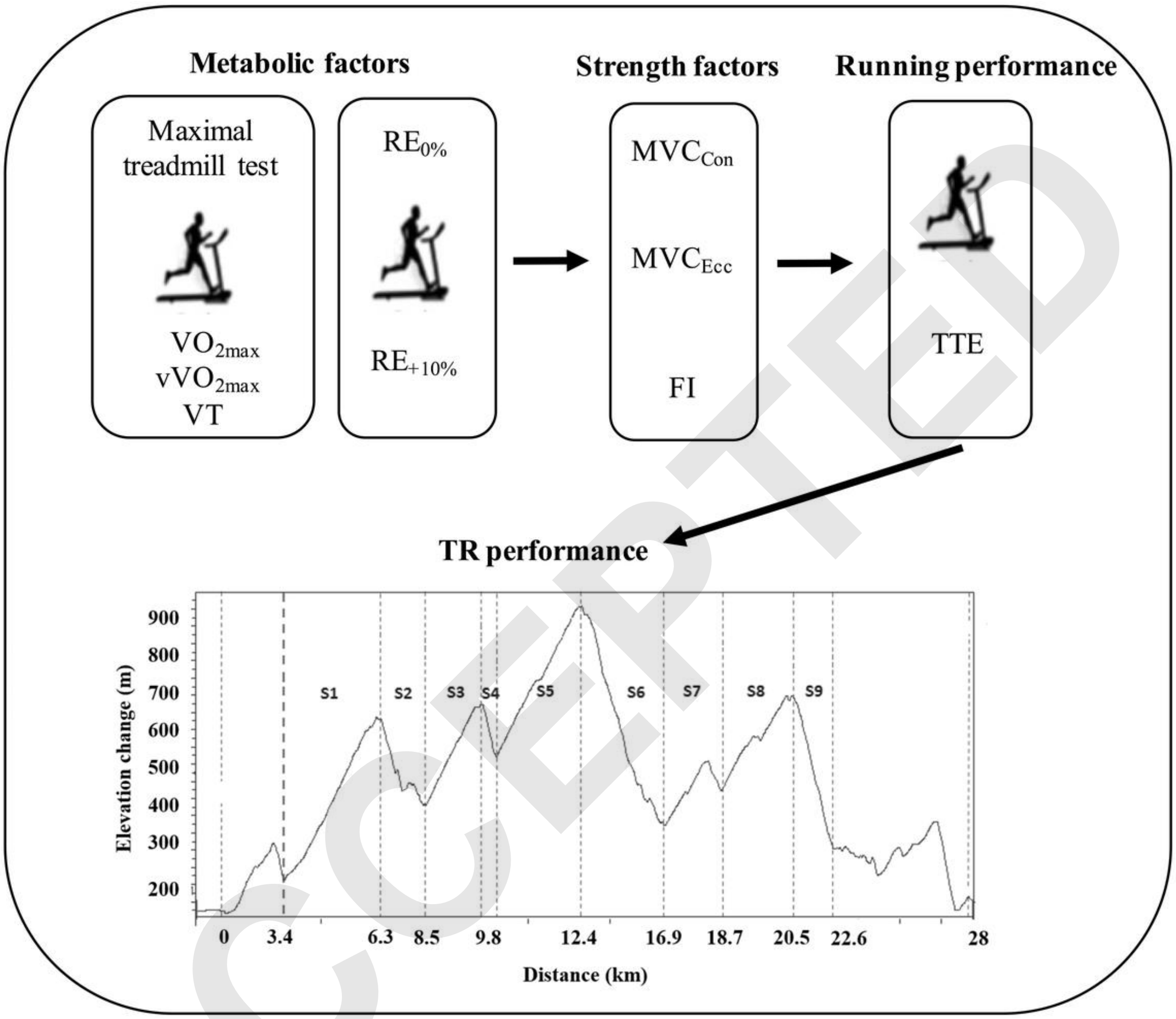

Metabolic factors
Strength factors
Running performance
Maximal treadmill test
VO_{2max}
vVO_{2max}
VT
$RE_{0\%}$
$RE_{+10\%}$
MVC_{Con}
MVC_{Ecc}
FI
TTE
TR performance
Elevation change (m)
900
800
700
600
500
400
300
200
S1
S2
S3
S4
S5
S6
S7
S8
S9
0
3.4
6.3
8.5
9.8
12.4
16.9
18.7
20.5
22.6
28
Distance (km)

Figure 2

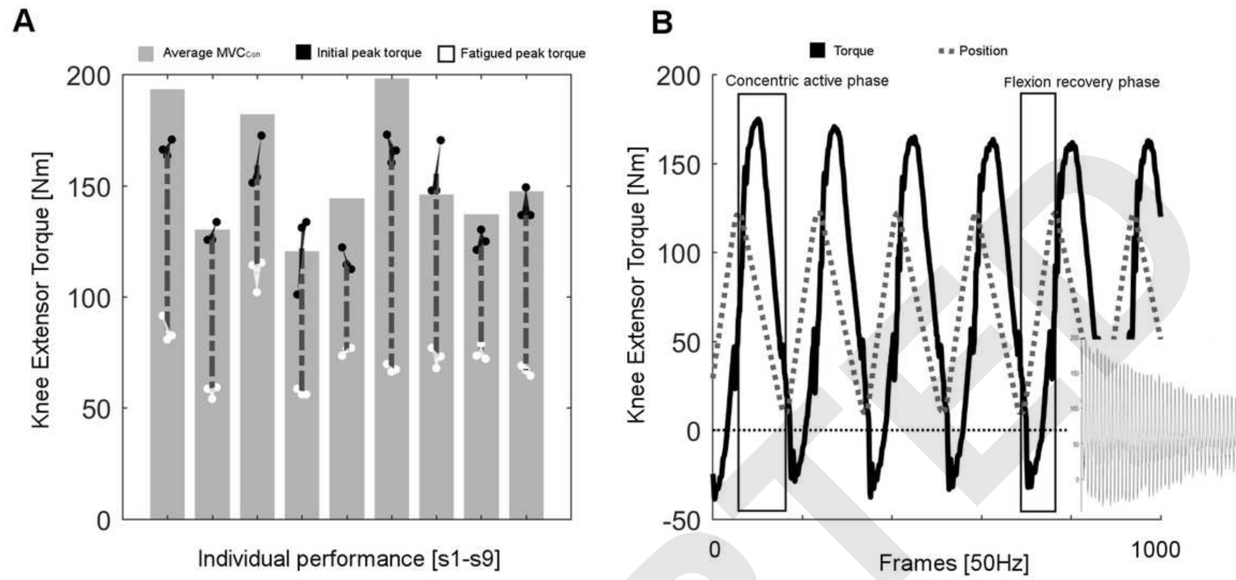
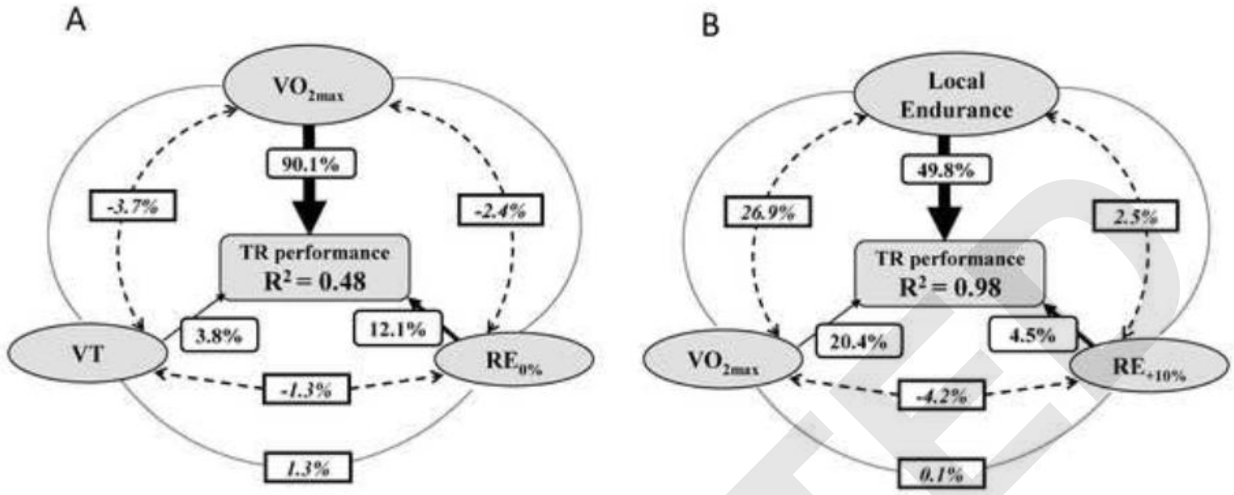

A
Average MVCCon
Initial peak torque
Fatigued peak torque
200
150
100
50
0
Knee Extensor Torque [Nm]
Individual performance [s1-s9]
B
Torque
Position
Concentric active phase
Flexion recovery phase
200
150
100
50
0
-50
Knee Extensor Torque [Nm]
0
1000
Frames [50Hz]

Figure 3



A
VO2max
90.1%
-3.7%
-2.4%
TR performance
R² = 0.48
VT
3.8%
12.1%
RE0%
-1.3%
1.3%
B
Local Endurance
49.8%
26.9%
2.5%
TR performance
R² = 0.98
VO2max
20.4%
4.5%
RE+10%
-4.2%
0.1%

Figure 4

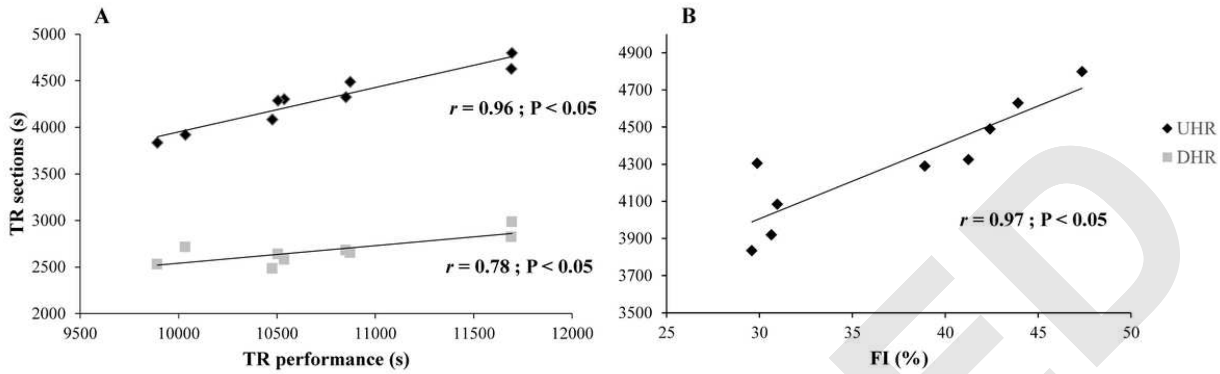

A
5000
4500
4000
3500
3000
2500
2000
TR sections (s)
9500
10000
10500
11000
11500
12000
TR performance (s)
r = 0.96 ; P < 0.05
r = 0.78 ; P < 0.05
B
4900
4700
4500
4300
4100
3900
3700
3500
25
30
35
40
45
50
FI (%)
r = 0.97 ; P < 0.05
UHR
DHR

TABLE 1. Running economy and muscular characteristics measured during laboratory-based sessions.

	Mean (SD)	Min	Max
$RE_{+10\%}$ ($J.kg^{-1}.m^{-1}$)	5.3 (0.6)	4.5	6.4
$RE_{0\%}$ ($J.kg^{-1}.m^{-1}$)	3.4 (0.3)	3.0	3.9
MVC_{Con} ($Nm.kg^{-1}$)	2.3 (0.3)	2.0	2.8
MVC_{Ecc} ($Nm.kg^{-1}$)	4.7 (0.6)	3.8	5.9
FI (%)	37.2 (7.0)	29.6	47.5

Values are presented as mean (SD). $RE_{0\%}$ and $RE_{+10\%}$: running economy normalized to body mass at level ground and +10% slope, respectively; MVC_{Con} and MVC_{Ecc}: maximal voluntary concentric and eccentric contraction torques, normalized to body mass; FI: fatigue index.

TABLE 2. Pearson product-moment correlations with TR performance and commonality matrix with unique and common effects for each independent variable.

	Correlation coefficients		Commonality coefficients for classic model		Commonality coefficients for adapted model	
Predictors	r	*P*	Unique	Common	Unique	Common
VO_{2max}	-0,76	0.03	0.43	-0.02	0.20	0.21
$\%VO_{2max}$ at VT	0.11	0.80	0.02	-0.02	-	-
$RE_{0\%}$	0.25	0.55	0.06	-0.01	-	-
$RE_{+10\%}$	0.21	0.63	-	-	0.04	-0.02
FI	0.91	<0.001	-	-	0.49	0.28

Unique and common effects for all independent variables (predictors) were identified throughout a commonality regression analysis applied to both the classic endurance running model and adapted model specific to TR performance.